Process Equipment Design

Prof. Shabina Khanam
Department of Chemical Engineering
Indian Institute of Technology - Roorkee

Lecture – 4
Basic Design Parameters - I

Hello everyone, welcome to the fourth lecture of week 1 of process equipment design course. In this lecture, we will cover basic design parameters to design heat exchangers. So basic design parameters topic I will cover in 2 lectures, lecture 4 and lecture 5. So, let us start with basic design parameters to design the heat exchangers.

Now, if I ask you that what is the basic equation in heat transfer because we are going to first design the heat exchanger equipment, you should understand the basic design equation and then whatever parameters involved in that equation that we will discuss one by one.

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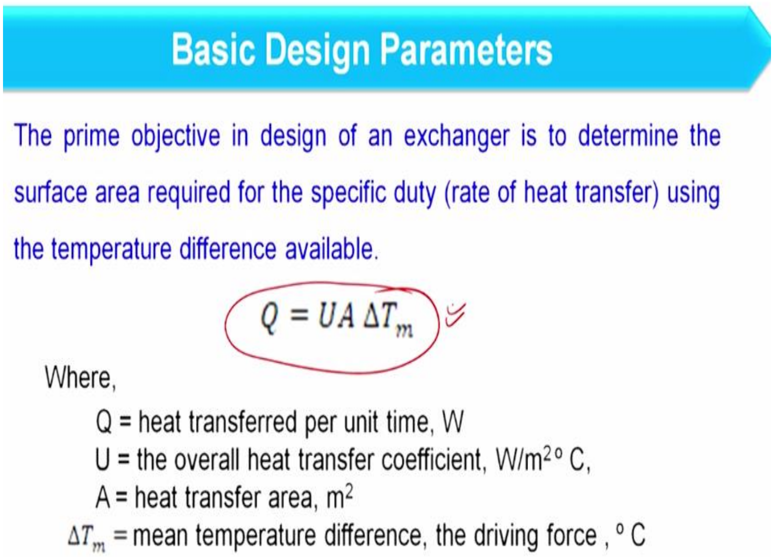

So, what is basic design equation as far as heat transfer is concerned? I hope that you all know that basic design equation for an exchanger is when we relate heat duty with heat transfer coefficient area and temperature difference. So, the basic design equation everybody knows if he or she is a chemical engineer that this is the basic design equation where Q = UA delta Tm.

Delta Tm sometimes we call as delta Tlm that is basically the log mean temperature difference, but here we are generalizing it mentioning delta Tm as a mean temperature difference that may be LMTD also. Now, when I consider this equation and if I ask you is there any other equation for heat transfer, your answer must be yes and what is that equation? There we relate Q = m Cp dT because as far as this Q is concerned Q is basically the heat duty.

Heat duty means the capacity of transferring heat from one fluid to another fluid and that should be in balance that is the m Cp dT of one fluid should be equal to m Cp dT to another fluid. So, as far as heat transfer is concerned, we have two basic equations. First is Q = m Cp dT and that Q = UA delta T men. So, as far as different parameters of this equation Q = UA delta Tm is concerned that all parameters you know very well U = overall heat transfer coefficient.

A we consider as the heat transfer area and delta Tm is the mean temperature difference and the driving force available in the heat exchanger. So, this is the basic design equation. Now, what would be the basic parameters then? Basic parameters will be when I consider Q, Q = m Cp dT. Now, in this equation am I able to play with any of the parameter, am I able to play with any of these parameters like can I change m, can I change Cp, can I change temperature difference?

The answer is no. Because whatever system is available to you that is up to from this temperature to this temperature you have to transfer the heat, you have to reduce the temperature of particular stream. The flow of the stream is this much and if you are fixing the stream you can already fixed the property of it and that is the Cp value, right. So, Q = m Cp dT you cannot play with it.

And similarly, if I consider Q = UA delta Tlm as you cannot change the temperature you cannot play with delta T mean, terminal temperatures of both extremes would be constant. So, you cannot play with delta T mean. However, you can make correlation between U and A. Correlation means U would be some factor into A I am not saying that, I am saying that you can make a relation or you can make the connection between U and A.

As you are changing U, you can change A. So, basic design equation in which different parameters are U, A and delta Tm. So, as I have told you, you can fix delta Tm, but how you will consider U overall heat transfer coefficient because this overall heat transfer coefficient is again a function of different factors. So, let me first focus on basic parameter of this equation that is overall heat transfer coefficient and then we will discuss delta T mean.

If I am fixing these two, we can already fix heat transfer area. So, heat transfer area is not the basic parameter you have to fix that you can understand as this is the design parameter because heat transfer area is a design parameter.

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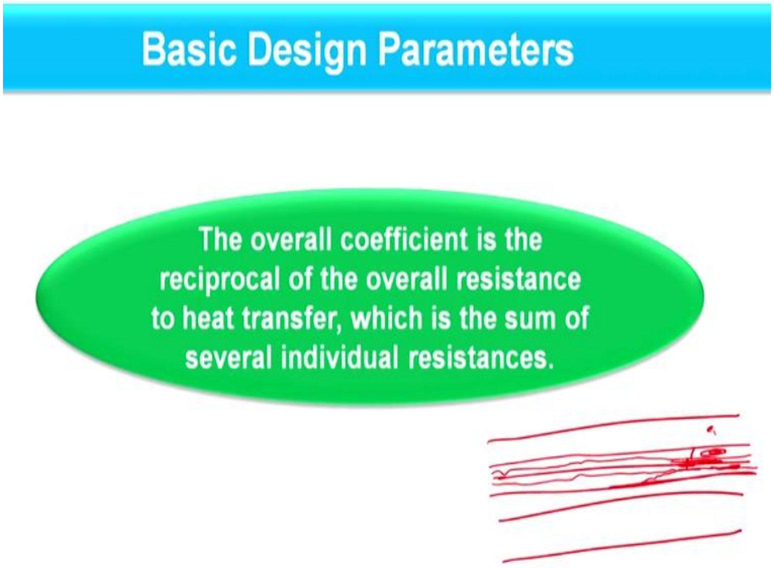

So, let us discuss with the overall heat transfer coefficient that is capital U. Now, if you see this overall heat transfer coefficient what it is basically? This is the reciprocal of overall resistances to transfer the heat, which is the sum of several individual resistances. Overall heat transfer coefficient is inversely proportional to the resistances. Whatever, like if I am having the resistance and as I am keep on increasing that resistance, I am putting extra hurdle in the path of transfer of heat and so the heat transfer will reduce.

As resistance will increase overall heat transfer will decrease and therefore overall heat transfer coefficient will decrease. So that you know very well that overall heat transfer coefficient is inversely proportional to overall resistances in the path of transfer of heat. Now, what these resistances are? If I am considering a pipe. Let us say this is the pipe in which I am considering heat transfer coefficient at outer surface of it.

Inside this one fluid is moving or outside this fluid is moving, you can understand this as a double pipe heat exchanger where this particular surface is the outer layer of inner pipe, inside this one fluid is already moving, fine. Now if I ask you what are the different resistances or how heat transfer will take place? To understand that you should understand the mechanism of heat transfer first.

Let us say on annular side we have hot fluid and inside the inner pipe we have cold fluid. Now annular side if I am having the hot fluid, the heat is first transferred from that hot fluid to the tube wall and then from tube wall to the inner side of the tube or to the fluid which is flowing inside the inner pipe, right. So, what are the resistances total? If I am considering a double pipe heat exchanger let us say like this and here I am having this double pipe, fine.

So if you consider this outer layer, outer surface of inner pipe, then what will happen? There must be some scale formation, at inner surface also there must be some scale formation. It will not be uniform, somewhere thickness is more, somewhere thicknesses less and above that we have the fluid film. So, as far as heat transfer is concerned first from this liquid, the fluid will come over here and then from in this layer we will have the transfer of heat through convection.

After that heat will transfer through this scale or dirt formation through conduction and after that we can have transfer of heat from wall to the inner surface through conduction and further we can have the resistance which is offered by the dirt formation at inner surface of inner pipe and after that we will have this formation of fluid inside the inner pipe. So, in this case we can have the heat transfer due to convection, fine.

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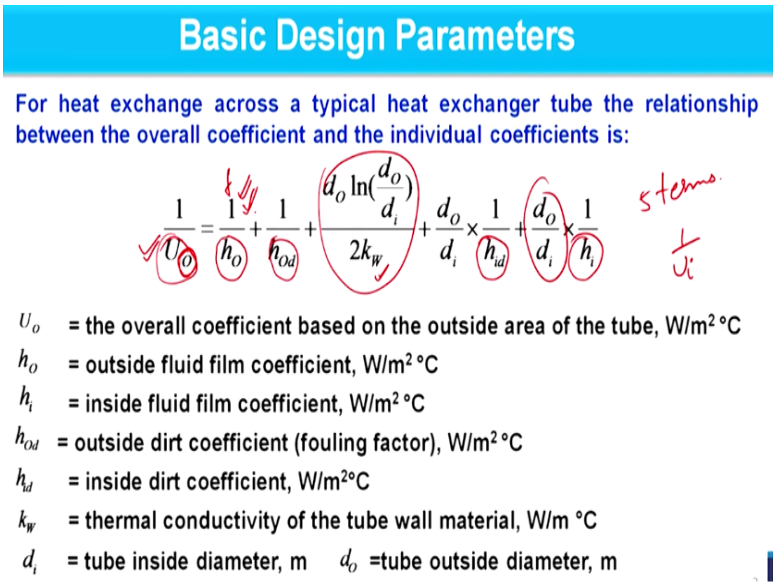

So if I ask you what are the total terms or parameters included in overall heat transfer coefficient when it is related to individual coefficient, right. So, the expression will be like 1 by U0 that is the overall heat transfer coefficient will be equal to the film heat transfer coefficient at outer layer of inner pipe and that is in the fluid that is with the fluid hOd is basically dirt factor, this is not basically dirt factor, this is heat transfer coefficient of dirt.

So, here we have this hOd is dirt coefficient which is available at outer surface of inner pipe, fine. Further I am considering conduction in the inner pipe material and where this kw is the thermal conductivity of the material do and di that you understand that is the inside dia and outside dia of the tube and further hid if I am considering hid is basically the dirt coefficient at inner side of inner pipe and similarly small hi is the inner coefficient due to convection at inside the pipe.

So, in this way we have total 5 terms. Now, what is this U0, capital U0. Capital U0 is overall heat transfer coefficient considering outer area, U0 means it is at the outside of the area. This is basically the outer area of tube. So, if I ask you what can be 1 by Ui, 1 by Ui means here we have a hi, right, and here we have h0 and we have di by d0 over here. In this way, we can consider 1 by Ui that is overall heat transfer coefficient at inner surface of the inner area of the tube.

So, I hope you understand the difference between U0 and Ui. Now, how I can calculate this U0? I can calculate this U0 once I know all these terms. If I know the individual heat transfer coefficient, dirt coefficient, thermal conductivity of the material, then only I can calculate overall heat transfer coefficient, right. But when we start the design of heat exchanger, I do not know anything about the exchanger except the temperature drop or temperature gain I have to consider along with the flow rates.

So, at that time I am not aware of di and d0, I am not aware of material of construction, h0, hi no parameter I aware of, right. So, in that case what I can do? In that case, I have to take some initial guess for overall heat transfer coefficient and how that initial guess can be taken?

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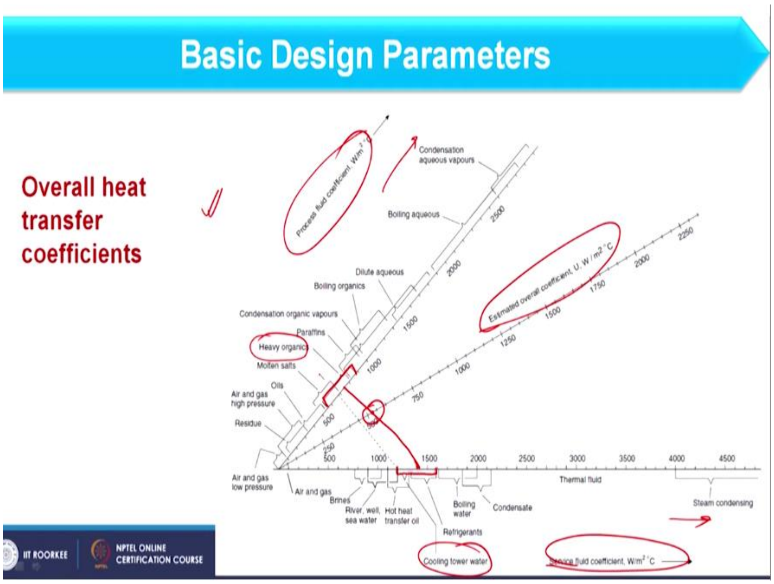

For that, we have this graph. In this graph, you see we have service fluid coefficient and process fluid coefficient. Now, what is service fluid, what is process fluid? Service fluid is basically that fluid which provides heat according to the requirement and process fluid is that fluid which temperature either increases or decreases as per the process requirement, fine. So, service fluid will be called when there will be the requirement from process fluid side.

Let us say we have to increase a process fluid from this temperature to this temperature, so we will provide a steam as service fluid. So you must understand what is the process fluid, what is the service fluid, fine. Now, let us say you know already about the process fluid. For example, if you have heavy organic as process fluid and let us say cooling tower water as service fluid.

There are different service fluids available and there are different process fluids available. Let us say you have chosen these two, then how you will consider overall heat transfer coefficient? To consider that if let us say I am having heavy organic range varies from this to this, right, this is the range of heavy organic, what I will consider then? I will consider the middle point of this, right.

Similarly, if I am considering cooling tower water, the complete range is this and I will select the middle of this. Now, I will join these two points using a straight line, here a straight line is not followed but you have to follow the straight line and wherever it will cut this center line, wherever it will cut this center line means this point, this will give overall heat transfer coefficient assumed value.

As if you see here this is the line for estimated overall coefficient. So, estimation based on these assumptions. So, to start the calculation because if you consider the design of heat exchanger first of all you have to calculate the area and then only you can calculate the tubes, etc. For that you should aware about the overall heat transfer coefficient. In that case, we have to assume the value and this estimated overall coefficient is nothing but the assumed value, right.

So, this graph will help you to assume the value of overall heat transfer coefficient as initial guess and this graph is available in volume 6, Richardson Coulson volume 6. I hope you all are aware with this book and in that book, there is one table also where we have the range of overall heat transfer coefficient depending upon different combinations of the fluids and the heat exchangers.

So you can use that table or this graph whatever you want. So, it will only give you a start, further when you will have all five terms in overall heat transfer coefficient you have to calculate the coefficient and compare with this assumed value. What is the criteria of comparing, etc., all that we will discuss in detail design of heat exchanger in subsequent lectures. So, overall heat transfer coefficient you have considered.

Further if you recall the overall heat transfer coefficient expressions, what are the terms? The hi and h0 that will depend on the heat transfer taking place in both fluids. For that we have different correlations, thermal conductivity of the material was a parameter but you cannot do anything with that because it will depend on the material whatever you are choosing for tubes, fine and next is we have to decide dirt factor also because it has hid and hOd, hid is the dirt coefficient at inner layer, hOd is dirt coefficient at outer layer.

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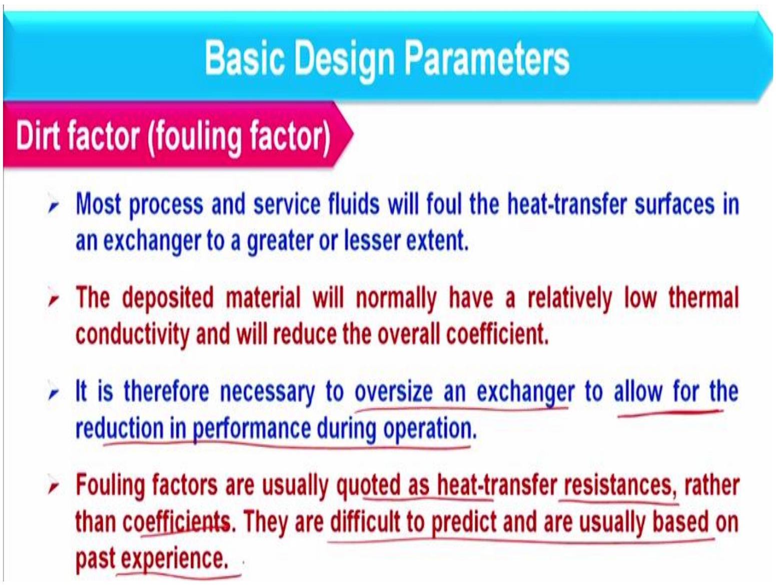

So, let us move towards discussion on dirt factor. How we will choose the dirt factor or fouling factor. For that most process and service fluids will foul the heat transfer surfaces in an exchanger to a greater or lesser extent. So, you cannot say that fluid will not foul the surface. Each fluid will have some tendency to foul the surface or to deposit the material over the surface, either it is lesser or greater.

So, whatever material is deposited that we call as dirt factor. Now, my point is how this dirt formation occur? How we can say that a scaling is formed or fouling occur in the system? To give an example let us say if I am dealing with water. So, usually what happens? As we increase the temperature solubility of the material in the liquid is increased, right. However, there are some fluids or there are some component for which solubility decreases with increase in temperature.

For example, if I am having water which has a scale formation component such as calcium ion, magnesium ion, etc. Now, what will happen? As the temperature increases, solubility increase, right, but after certain time or after certain temperature what will happen? Solubility decreases and that temperature in water is around 40 degrees Celsius. So, beyond 40 degrees Celsius, the solubility of these material decreases, right.

Now, what will happen after that? Once solubility will decrease, precipitation of the material will start and material will start depositing over the heat transfer surface. So, that example I have taken with water, other fluids also have similar tendency, right. So because of increase in temperature, we can face the problem of scaling in the material because 40 degree or somewhere near to that is very less temperature and heat exchangers usually we operate at very high temperatures, right.

So, we have to be careful while designing because you cannot change the nature of the fluid, whatever fluid you want to use you have to use. You have to design in such a way so that the bad tendency of the fluid can be avoided. Now, how I can do that? Let me tell you like what is the effect of that dirt factor? When scaling formation occur or dirt formation occur over the tube surface or over the metal surface, then it will offer an extra resistance.

Therefore, it is included in overall heat transfer coefficient expression, fine. Because of this resistance overall heat transfer coefficient decreases, and if you remember the overall heat transfer coefficient expression it has 1 by hOd, 1 by hid that is the coefficient of dirt factor that will be reciprocal to dirt factor, heat transfer coefficient of dirt is reciprocal to the dirt factor value, right.

So as dirt factor increases, overall heat transfer coefficient decreases. So, where I am compensating basically, if I am considering dirt factor which reduces overall coefficient, and if you are considering Q = U A delta Tlm what I am doing basically I am increasing the area, right, because I am decreasing overall heat transfer coefficient. So, if I am doing so what I am doing basically? I am oversizing the heat exchanger, right.

I am oversizing the heat exchanger because I am already considering lesser heat transfer coefficient and this oversizing will compensate the reduction in performance during operation. Because what will happen? Because whatever surface I am considering it will have scale formation in due operation. If I am oversizing the heat exchanger, then the dirt formation will be there, but it will occur for longer time as compared to lesser heat transfer area.

So fouling factors are usually quoted as heat transfer resistances rather than coefficients. They are difficult to predict and are usually based on past experience because when you are designing a heat exchanger at that time you are calculating 1 by U0 considering all five parameters, but at that time your exchanger is not existing. So, how dirt that factor you can consider.

That you can consider based on past experience that if I am having this fluid it will give that much dirt factor and accordingly how much oversize of exchanger, I have to do that I can decide from the beginning, right. So, choosing right dirt factor value is important in design of heat exchanger.

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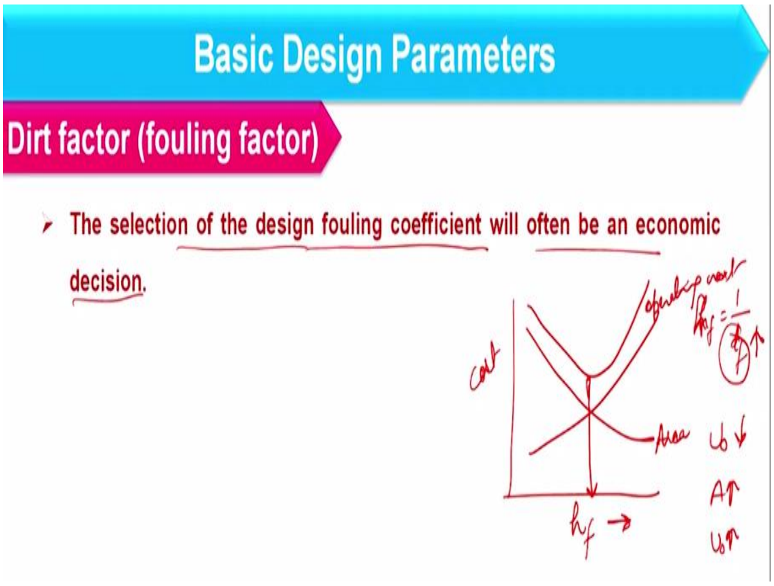

As far as selection of design of fouling coefficient it will be an economic decision. How this will be an economic decision? Now, let me explain that with the help of one graph, let us say here I am having a graph where on y axis I am considering cost and here let us say I am having dirt coefficient hf. Now, what will happen, hf is what? The hf is dirt coefficient, fine, and hf is basically the reciprocal of dirt factor.

Now as dirt factor increases, hf decreases. And once hf decrease, overall heat transfer coefficient will also decrease. Now, once overall heat transfer coefficient decrease, area will increase, right. So, as dirt factor increases, fine, hf will decrease and area will increase. So, I am having capital investment like this because I'm having more and more heat transfer area as hf will decrease in this direction.

However, if I am considering hf and in this direction if I am considering that hf is increasing, if hf is increasing, what is the meaning of that? Overall heat transfer coefficient will increase, right. So, heat transfer area will decrease like this. So, overall heat transfer area will decrease as hf will increase. Now if I am having lesser heat transfer area, it will have more and more tendency to foul again and again.

It will have more and more tendency to foul again and again, what is the meaning of that? If I am having lesser area it will be fouled in less time. It means maintenance cost will increase or we can say the cycle time in which the cleaning of exchanger should take place it will decrease. Cycle time decrease means the maintenance cost will increase or we can consider as the operating cost will increase, right. This is the area and this is the operating cost.

So, optimum hf will be like this where am having minimum overall cost, so that would be this factor. So, in this way we can consider that dirt factor is an economic decision.

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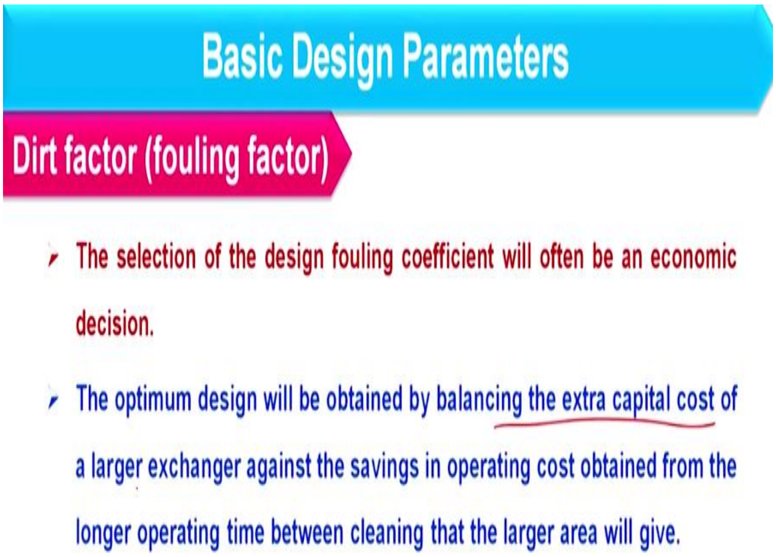

So, the optimum design will be obtained by balancing the extra capital cost of larger heat exchanger against the savings in operating costs obtained from longer operating time between cleaning that larger area will give. So, in that way I hope you understand how to select the optimum dirt factor. And if you consider the graph which I have just discussed that there are two factors, first is capital investment and second is the operating cost.

So these two factors work opposite to each other as hf will increase, right. So this is the perfect problem for optimization. So we can consider optimum hod value by balancing the capital investment due to higher area and by balancing the operating cost due to longer cleaning time if I increase the area, right. So in that way, I can choose the optimum fouling coefficient, fine.

Next option is though we are providing larger area but definitely it will go to maintenance after certain time. So what will happen at that time? My plant cannot remain at shutdown position for longer duration, so the better option is I have to use duplicate equipment fine. So, let us say if I am dealing with 6 heat exchangers, I have to consider 7 heat exchangers, one heat exchanger will remain at standby position all the time.

So, whenever the requirement occurs like if heat exchanger is not working, we can use that heat exchanger and same thing will occur with other equipment like evaporator, reactors, etc. So, duplicate equipment is must when I am dealing with dirt factor problem.

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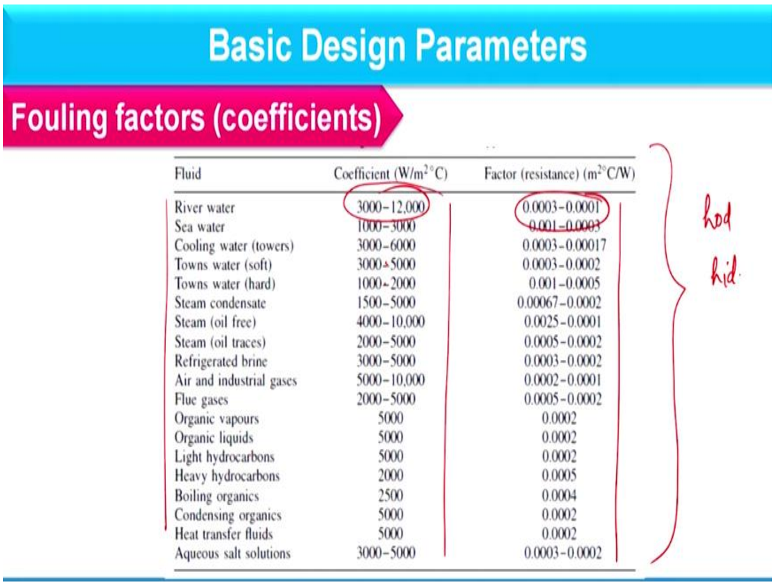

Fluid	Coefficient (W/m²°C)	Factor (resistance) (m²°C/W)
River water	3000–12,000	0.0003–0.0001
Sea water	1000–3000	0.001–0.0003
Cooling water (towers)	3000–6000	0.0003–0.00017
Towns water (soft)	3000–5000	0.0003–0.0002
Towns water (hard)	1000–2000	0.001–0.0005
Steam condensate	1500–5000	0.00067–0.0002
Steam (oil free)	4000–10,000	0.0025–0.0001
Steam (oil traces)	2000–5000	0.0005–0.0002
Refrigerated brine	3000–5000	0.0003–0.0002
Air and industrial gases	5000–10,000	0.0002–0.0001
Flue gases	2000–5000	0.0005–0.0002
Organic vapours	5000	0.0002
Organic liquids	5000	0.0002
Light hydrocarbons	5000	0.0002
Heavy hydrocarbons	2000	0.0005
Boiling organics	2500	0.0004
Condensing organics	5000	0.0002
Heat transfer fluids	5000	0.0002
Aqueous salt solutions	3000–5000	0.0003–0.0002

Now, here I am having a table, this is again available in Richardson Coulson volume 6. Here I am having depending upon the type of fluid we can have dirt coefficient as well as dirt factor. So, you see dirt factor are inversely proportional to the coefficient and here we are given the range of coefficient as well as factor for a given fluid. So to start with hOd and hid can be taken as mean value of this, right. So, in this way according to the fluid I can choose the dirt factors.

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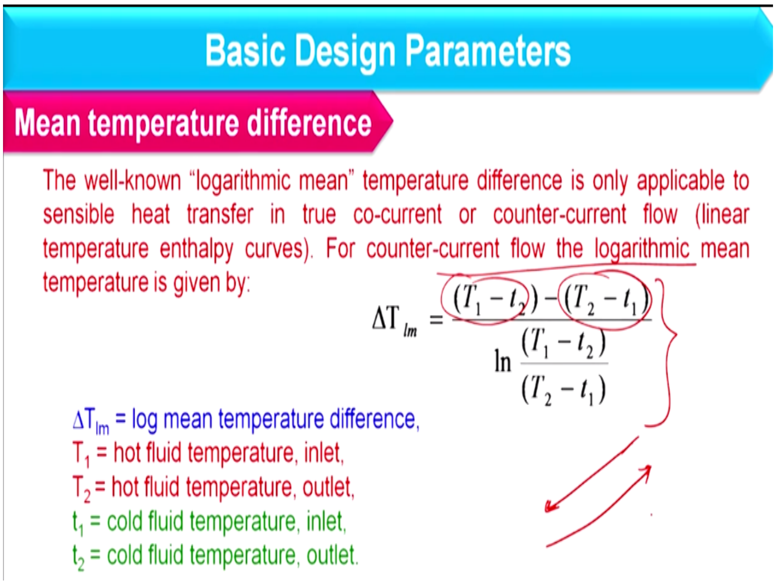

So next parameter we are going to discuss is the mean temperature difference. So, you already have seen how to select overall heat transfer coefficient, dirt factor and then the mean temperature difference. Mean temperature difference usually in a heat exchanger we consider logarithmic mean temperature difference because we have co-current and counter-current heat transfer.

So for counter-current flow, logarithmic mean temperature is given by this expression, temperature approach of one side and this is temperature approach of another side and then log of these temperature approaches. So, I think this equation you are aware with this very well. So, this is for counter-current. Now, my point is why I am considering log mean temperature difference because continuously change in temperature occur in both fluids.

If I draw the profile, hot fluid will move like this, cold fluid will move like this, so that may be linear, that may be nonlinear. If linearity will occur, we can consider simple LMTD. If linearity will occur, we can consider simple arithmetic mean. However, here nonlinearity may also occur along the length, therefore we consider log mean temperature difference. So, this is the equation when you are considering counter-current flow.

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Basic Design Parameters

Mean temperature difference

The equation is the same for co-current flow, but the terminal temperature differences will be $(T_1 - t_1)$ and $(T_2 - t_2)$. In most shell and tube exchangers the flow will be a mixture of co-current, counter-current and cross flow.

The usual practice in the design of shell and tube exchangers is to estimate the "true temperature difference" from the logarithmic mean temperature by applying a correction factor to allow for the departure from true counter-current flow:

$$\Delta T_m = F_t \Delta T_{lm}$$

Where, ΔT_m = True temperature difference

F_t = LMTD correction factor

And here we can consider co-current flow LMTD also where temperature differences at one side is capital T1 – small t1 and capital T3 – small t2. So, in most of the heat exchanger shell and tube heat exchanger, we have co-current and counter-current and cross flow as well. Let us say if I am considering one to pass shell and tube heat exchanger, in one tube there may be co-current, in another fluid there may be counter-current.

And when the fluid is entering from the shell nozzle to shell side, it will cross the fluid which is flowing in tubes, so there cross flow will also occur. So, usually in shell and tube heat exchanger, we have mixed flow where co-current and counter-current and cross flow all 3 flow occurs simultaneously. And therefore, whatever mean temperature difference we have calculated it will not work, it will work only when there is co-current or counter-current, but here we have the mixture.

So, in that case, we found some reduction in LMTD value and that reduction will be counted considering another factor and that factor is Ft factor. If you see delta Tm = Ft into delta Tlm, so that is basically the log mean temperature difference for counter flow, this is for counterflow Ft LMTD correction factor. So maximum value of Ft will be 1 and therefore we can consider that Ft will give a lesser mean temperature difference in comparison to LMTD.

The reason is very simple because it has mixed flow, not a particular flow. So, here I am stopping this lecture. I will continue with details of Ft correction factor and other parameters in next part of this lecture that is lecture 5. So, that is all for now. Thank you.